

Nuclear Thermal Rocket - Arc Jet Integrated System Model

With the development of commercial space flight and the progression of the commercial crew program, many low earth orbit activities are transitioning to the private sector. This will soon include transportation of astronauts to and from the international space station. As this transition takes place, NASA is becoming more focused on deep space exploration. There are many different concepts and destinations for deep space exploration that have been discussed in the ongoing public discussion. Some examples include missions utilizing Lagrange points, and visiting or recovering an asteroid. The destination which has long since captured the imagination is Mars. There are several different concepts concerning the future exploration of Mars, including concepts involving missions to the moons Phobos and Deimos. Manned missions to Mars are very ambitious and will require the development of many technologies and thorough logistical planning.

Deep space exploration missions, such as missions to Mars, face many technological challenges that must be considered and resolved far in advance of any mission. For this reason, current technology development is critical to achieving NASA roadmap goals for deep space exploration in our life time. Many of these challenges are in regards to the development of propulsion systems that can meet mission requirements. The propulsion system for the transfer vehicle that will carry astronauts and equipment to Mars must meet a number of requirements, including operating as efficiently as possible and providing enough thrust for the astronauts to reach Mars in a reasonable amount of time.

A manned mission to Mars will require a payload much larger than anything ever before sent to the Martian surface. This will likely be supported by smaller cargo vehicles sent in advance of the astronauts. While the cargo missions can operate over longer periods of time and utilize highly efficient solar powered propulsion systems, the manned vehicle must traverse to Mars at a much faster rate. The manned Mars transfer vehicle will be required to operate as efficiently as possible while still providing enough power and delta V (velocity vector change due to the thrust of the propulsion system) to achieve desired flight times between Earth and Mars. The efficiency of the propulsion system relates how much thrust is gained from a unit mass of propellant. The large quantities of thrust and delta V needed in this mission amounts to significant quantities of propellant that must be lifted into orbit, carried, and stored (cryogenically). The cost and achievability of a manned mission to Mars will be sensitive to the required quantity of propellant and thus the efficiency of the propulsion system. The efficiency can be characterized by the term specific impulse (I_{sp}). Specific impulse is defined as the ratio of total impulse to mass of consumed propellant and has units of seconds. The best chemical engines available today provide high thrust but specific impulse values of approximately 400 to 450 seconds at best. Electric propulsion systems currently available are highly efficient with specific impulse values in the thousands, but are low thrust systems. This results in long flight times. Nuclear thermal propulsion systems; however, are capable of providing high thrust at a specific impulse that is double that of the best chemical engines (I_{sp} in the 800 to 900 seconds range). This makes nuclear propulsion an attractive option for a Mars transfer vehicle.

The use of nuclear power a spacecraft's propulsion system has gained renewed interest in recent years as the National Aeronautics and Space Administration (NASA) is progressing down a developmental and operational path to sending astronauts to Mars. Research started on nuclear

propulsion systems at Los Alamos Scientific Laboratory under Project Rover in the 1950's. The Nuclear Engine for Rocket Vehicle Application (NERVA) program, which was a joint effort between NASA and the Atomic Energy Commission, was a development program for a nuclear thermal propulsion system. Rover/NERVA developed and tested several reactor and nuclear thermal engine system designs. This program ended in the early 1970's. In recent years, some of the work has been design cycle studies, power balance models, system trades, planning for logistics as well as ground tests, and component technology development. It is apparent based on past work that even with ideal technology development, logistics, and resources the performance of a nuclear thermal propulsion system will still require a large quantity of propellant and thus a significant operational and resource intensive undertaking. It is therefore desirable to increase the performance of a nuclear thermal propulsion system in any way we can despite the fact that it is more efficient at equivalent power levels than chemical engines.

One concept to further improve the performance of a nuclear thermal propulsion system is to augment the energy in the propellant prior to expansion through a nozzle with an electric propulsion system. An Arc Jet is an example of such a system. Heat augmentation systems, such as this, have been considered impractical in the past due to the difficulty in generating large quantities of electrical energy. Most of these difficulties stem from the assumption that huge radiators would be required to dissipate the large amount of waste heat resulting from the cycle power conversion process. A way around this is to reject the heat directly to the propellant in an open loop configuration. This is made possible by the energy rich reactor of nuclear thermal propulsion systems. A conventional nuclear reactor in the propulsion system is limited in the energy that can be extracted by the rate of heat transfer to the propellant and the temperature limits of the reactor materials. Consequently, the nuclear reactor is capable of producing far more energy than can be extracted.

The concept considered in this work extracts additional energy from the reactor by passing the propellant through the reactor twice. In the first pass, the propellant is heated by the reactor before entering the turbine portion of a turbopump. The flow is expanded across the turbine generating power for the pump and excess power transferred to a generator. The generator power the arc jet. After the flow exits the turbine, it reenters the reactor where it is once again heated. Upon exiting the reactor the second time the flow passes through the arc jet, which imparts the additional energy from the generator and is expanded through a nozzle to produce thrust. The additional energy extracted from the reactor and added to the propellant will significantly improve the specific impulse albeit with somewhat lower thrust to weight ratios.

In regards to the concept previously discussed, this endeavor has attempted to accomplish several things. First, a power balance is developed based upon realistic performance and efficiency of current component technologies. Second, the dissociation of hydrogen (H_2) in the arc jet based on high temperature arc jet test data taken in the test area at NASA Marshall Space Flight Center is investigated. Specific impulse is inversely proportional to the square root of the molecular weight of the propellant species. Therefore, when H_2 dissociates to H and the molecular weight of the propellant species divides by 2, the specific impulse is increased. Third, develop a concept reactor layout to illustrate the multiple passes of the propellant through the reactor. Fourth, a rough optimization is performed. Finally, the work is tied together by determining the expected increase in specific impulse along with the approximate engine thrust to weight ratio. Initial calculations show a several hundred degree Kelvin increase from the reactor exit (second pass) to the nozzle inlet. The temperature increases improves

with efficiency of components. The nozzle inlet temperature is expected to range from 3200 to 3700 Kelvin for varying efficiencies and increases with reactor inlet pressure. This is in comparison to reactor outlet temperature of 2800 Kelvin. This considerable temperature increase translates to more energy available for conversion to thrust, thus increasing the efficiency and specific impulse of the propulsion system. This work will be discussed in further detail in the accompanying paper.